Nonmonotonic Temperature Dependence of the Thermal Hall Angle of a $YBa_2Cu_3O_{6.95}$ Single Crystal

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We have performed high-resolution measurements of the magnetic field (0 T $\leq B \leq$ 9 T) and temperature (10 K $\leq T <$ 140 K) dependence of the longitudinal and transverse Hall thermal conductivity of a twinned $YBa_2Cu_3O_{6.95}$ single crystal. We have used and compared two recently published methods to extract the thermal Hall angle $\theta_H(T,B)$. Our results indicate that $\cot(\theta_H)$ varies quite accurately as T^4 in the intermediate temperature range $\sim 0.3 < T/T_c$. It shows a well defined minimum at $T_m \simeq 20$ K which resembles that observed in the c-axis microwave conductivity. The electronic part of the longitudinal and the transverse thermal conductivity show the scaling behavior for transport properties predicted for d-wave superconductors in the temperature range ~ 18 K $\leq T \leq 30$ K.

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1. Introduction

A characteristic feature of the high-T_c superconductors (HTS) is the T^{-2} temperature dependence of the normal state Hall angle $\tan(\theta_H)$ which has been explained by Anderson within the framework of the Luttinger liquid theory.[1] Recently performed thermal Hall conductivity measurements on $YBa_2Cu_3O_x$ (Y123) single crystals at $T < T_c$ suggest that such a behavior would extend down to ~ 50 K.[2,3] Obviously the T^{-2} dependence cannot continue to arbitrarily low temperatures since it would imply an infinite scattering time or mean free path for the quasiparticles. Nevertheless,

it is unclear from literature which is the temperature dependence of the Hall angle below T_c and at which temperature the monotonic temperature dependence breaks down. Apart from a possible saturation of $\tan(\theta_H) \propto l^*(T)$ (an effective mean free path of quasiparticles) at low enough temperatures, there are at least two more reasons to expect a deviation from a monotonous temperature dependence at low temperatures. (1) Theory predicts a maximum in $\theta_H(T)$ at low enough temperatures due to a crossover from holon non-drag regime to localization.[4] (2) Electrical transport measurements performed on underdoped $YBa_2Cu_3O_{6.63}$[5] and Zn-doped $YBa_2Cu_3O_{7-\delta}$[6] crystals as well as in $Bi_2Sr_2Ca_{n-1}Cu_nO_y$ thin films[7]suggest that the temperature dependence of the (electrical) Hall angle $\tan(\theta_H) \propto \tau_H/m_H$ (τ_H is the Hall scattering time and m_H the effective mass of the quasiparticles responsible for the Hall signal) has a maximum at or near the temperature at which the pseudogap opens. Experimental evidence accumulated over the last years suggests also that the opening of a pseudogap can take place below the superconducting transition temperature affecting the electronic properties of HTS,[8,9] although its nature and its relationship to superconductivity are not yet well understood. Whereas the electrical Hall angle can hardly be measured at $T \ll T_c$, the thermal transport is suitable for the low temperature studies.

Below the superconducting critical temperature T_c and decreasing temperature, the in-plane longitudinal thermal conductivity κ_{xx} in HTS increases and shows a maximum between $0.3T_c < T < 0.9T_c$. This behavior is attributed nowadays mainly to the increase of the electronic contribution $\kappa_{xx}^{\mathrm{el}}(T)$ due to the increase in the quasiparticle-quasiparticle relaxation time τ. It appears that the increase in τ decreasing T overwhelms the decrease of the density of quasiparticles due to their condensation in the superconducting state. Pioneer work on the thermal conductivity of $YBa_2Cu_3O_7$ (Y123) crystals[10] as well as thermal Hall effect measurements[11,12,2,3] provide strong evidence for this interpretation. Regarding the difference between the Hall $\tau_H(T,B)$ and diagonal $\tau(T,B)$ relaxation times we note that whereas τ shows a monotonic enhancement decreasing T below T_c, τ_H/m_H appears to be unaffected by the superconducting transition.[2,3]

The difficulty to describe the behavior of the thermal conductivity and to obtain from the experimental data the temperature and field dependence of the Hall angle resides mainly in the method to separate the electronic contribution $\kappa_{xx}^{\mathrm{el}}$ from the measured total thermal conductivity. This is due to the relatively large phonon contribution to the thermal transport in HTS. Basically two methods for this separation have been treated in the literature. One method is based on a phenomenological description of the field dependence of $\kappa_{xx}(T,B)$, introduced first by Vinen et al.[13] and used in Refs.[14,15,3] to estimate $\kappa_{xx}^{\mathrm{el}}(T)$. The other, apparently more elegant method

presented by Zeini et al.,[2] is based on simultaneous measurements of the longitudinal and transverse thermal conductivity and the assumption of a field independent Hall relaxation time.

We note that the experimental error of the published data of the thermal Hall angle leaves its true temperature and field dependence not well defined below T_c. In this work we obtain the temperature dependence of $\theta_H(T,B)$ down to $\sim$ 10 K using high-resolution experimental data of κ_{xx} and κ_{xy} and the two recently proposed separation methods. We will show that the ratio m_H/τ_H follows a $(T/T_c)^4$ dependence that agrees with the temperature dependence of the scattering rate obtained from longitudinal thermal conductivity measurements.

2. Sample and experimental details

For the measurements we have used a twinned, nearly optimally doped $YBa_2Cu_3O_{6.95}$ single crystal with dimensions (length $\times$ width $\times$ thickness) $0.83 \times 0.6 \times 0.045$ mm^3 and $T_c = 93.4$ K. The use of a twinned crystal, with twinning planes parallel and perpendicular to the heat current, allows us to apply both separation methods described below, as well as to rule out the influence of orthorhombicity on the heat transport properties. The temperature and field dependence of κ_{xx} for this crystal have been recently measured below and above T_c with a relative accuracy of 10^{-4}.[16] The transverse thermal conductivity has been determined using the relation $\kappa_{xy} = \kappa_{xx}\Delta_y T/\Delta_x T$, where $\Delta_x T$ is the applied thermal gradient in x direction and $\Delta_y T$ is perpendicular to it when a magnetic field is applied in the z or $-z$ direction (parallel to the c-axis of the crystal). Because of twinning we have assumed that $\kappa_{xx} = \kappa_{yy}$. The temperature gradients were measured with a previously field- and temperature-calibrated type E thermocouples.[17] Their voltages were measured with a dc picovoltmeter which allowed a resolution of $\sim$ 30 μK at 100 K ($\sim$ 60 μK at 10 K). The short time (2 h) temperature stability of the sample holder was 50 μK, for more details see Refs.[16,17]

In all the temperature range (10 K $\leq T \leq$ 140 K) we have applied relatively small temperature gradients along the sample, typically $\Delta_x T \leq 300$ mK, in order to diminish smearing effects in the T-dependence of the measured properties. $\Delta_y(T,B)$ was determined from the difference $[\Delta_y(T,B) - \Delta_y(T,-B)]/2$ to eliminate offset contributions. The thermal Hall effect was measured as a function of temperature at constant B and $-B$ in the field-cooled state of the sample in order to rule out pinning effects.[16] The influence of the pinning of vortices to the Hall effect in the mixed state of superconductors should be considered seriously and carefully minimized,

specially at low temperatures.[18] We have checked the results measuring also the field dependence of κ_{xy} at constant selected temperatures. We have obtained very good agreement between both methods.

3. Results

Figure 1 shows the longitudinal κ_{xx} and transverse κ_{xy} thermal conductivity as a function of temperature at different constant applied fields. The overall $T-$dependence as well as the absolute value of those properties agree well with published results.[12,2] From these data we may obtain τ_H/m_H if the electronic contribution $\kappa^{\mathrm{el}}_{xx}(T)$ is known since according to the usual definition

$$\frac{\tan(\theta_H)}{B} = \frac{e\tau_H}{m_H} = \frac{\kappa_{xy}}{B\kappa^{\mathrm{el}}_{xx}}\,. \tag{1}$$

As in Ref.[2] our data also show that, in good approximation, $\partial(\kappa_{xy}/B)/\partial B \propto \partial\kappa_{xx}/\partial B$ in the whole measured temperature range. This fact was used by Zeini et al.[2] to estimate the Hall relaxation time assuming that κ_{xy} and $\kappa^{\mathrm{el}}_{xx}$ have a similar field dependence, neglecting the field dependence in τ_H/m_H or in the rest contribution to the thermal conductivity. Following Ref.[2] for a pair of values of field (B_i, B_j) with $B_i \neq B_j$ we can write

$$\frac{\kappa_{xy}(B_i)}{B_i} - \frac{\kappa_{xy}(B_j)}{B_j} = \frac{\tan(\theta_H)}{B}(\kappa_{xx}(B_i) - \kappa_{xx}(B_j))\,. \tag{2}$$

Taking pairs of points at low fields we can also calculate the initial Hall slope $\lim_{B\to 0}\kappa_{xy}/B$. This quantity is depicted in Fig. 2. We note that $\lim_{B\to 0}\kappa_{xy}/B$ increases two orders of magnitude below T_c reaching a maximum at 40 K.

In Fig. 3(a) we show $\tan(\theta_H)/B$ obtained using (2) for two pairs of fields and also from a linear regression considering the data at all fields. The results in Fig. 3(a) indicate that τ_H/m_H clearly deviates from a T^{-2} dependence and shows a maximum at $T_m \simeq 20$ K.

The results in Fig. 3(a) also indicate that $\tan(\theta_H)/B$ depends slightly on the pairs of fields used to compute it and decreases the larger the field of the chosen pair. It appears that the values obtained from the linear regression would provide $\tan(\theta_H)/B$ at $B \to 0$. The Zeini et al. approach is based on the assumption of a field independent τ_H/m_H or, in other words, a strictly linear field dependence for $\tan(\theta_H)$. Deviation from this assumption can be proved using the second separation method[14,3] to obtain $\kappa^{\mathrm{el}}_{xx}$ from the experimental data. Therefore, we use the second separation method in order to show that the temperature dependence of $\tan(\theta_H)$ at low enough fields is independent of the assumption of a field independent τ_H/m_H.

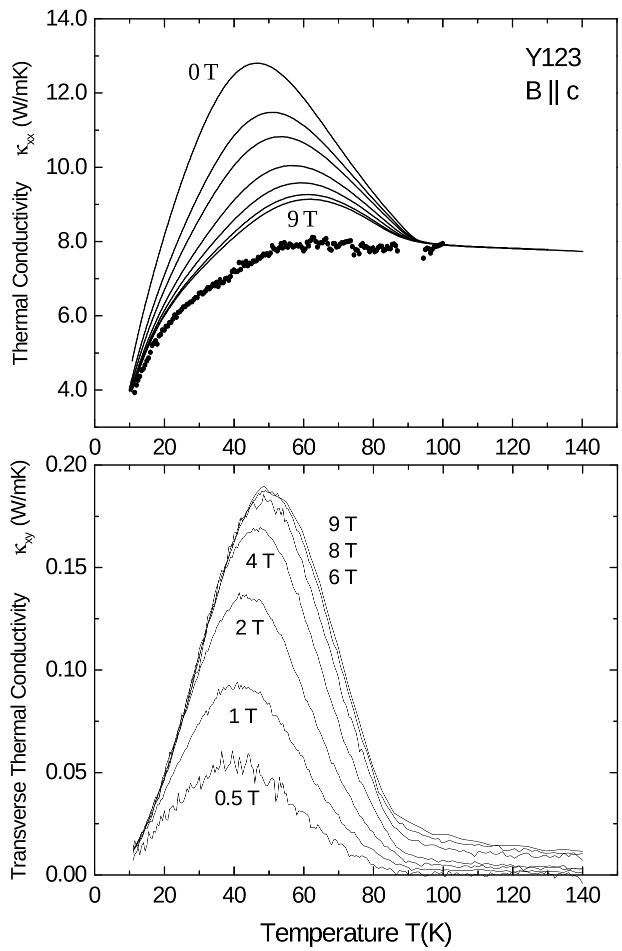


Fig. 1. Longitudinal (upper figure) and transverse (lower figure) thermal conductivity as a function of temperature at constant applied fields. The curves in the upper figure (from top to bottom) were obtained at $B = 0, 1, 2, 4, 6, 8, 9$ T. The close symbols represent the phonon or rest contribution to the total thermal conductivity.

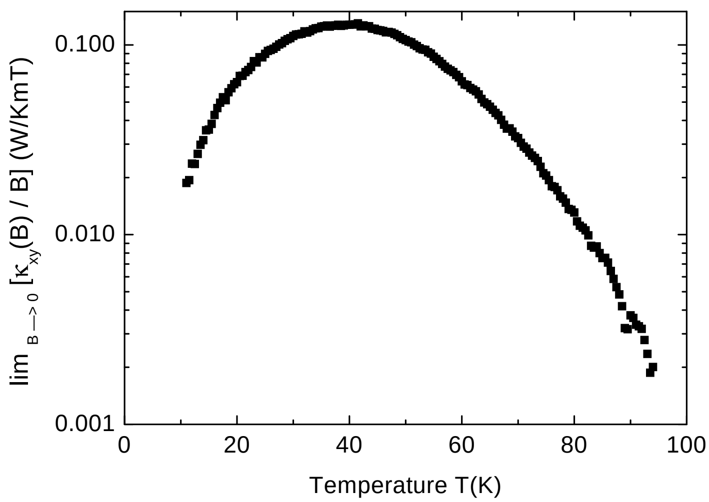


Fig. 2. Initial Hall slope $\lim_{B\to 0} \kappa_{xy}/B$ as a function of temperature.

As it was shown recently,[16] in agreement with Ref. 3, the field dependence of κ_{xx} (for $B||c$-axis) at all temperatures below T_c can be very well fitted assuming

$$\kappa_{xx}(T,B) = \kappa_{xx}^{\rm ph}(T) + \frac{\kappa_{xx}^{\rm el}(T)}{1+\beta_e(T)B}\,, \tag{3}$$

where $\beta_e(T)$ is proportional to the zero-field electronic mean-free-path (or the longitudinal relaxation time) of the quasiparticles.[11,14] Fitting the field dependence of $\kappa_{xx}(B)$ at different constant temperatures we can separate the electronic contribution and calculate $\tan(\theta_H)/B$ as a function of temperature at different applied fields. These results are shown in Fig. 3(b). At low fields, the temperature dependence of $\tan(\theta_H)/B$ resembles that obtained with the other separation method, specially the maximum at ~ 20 K, compare Figs. 3(a) and (b). We see also clearly that $\tan(\theta_H)/B$ decreases with field in the whole temperature range below T_c. Note that at high enough fields the maximum at $T \simeq 20$ K vanishes. Our data agree reasonably well with those we get using the data from Ref.,[3] see Fig. 3(b). We note that the data of Ref.[3] show a maximum in $\tan(\theta_H)/B$ at $T \sim 45$ K and at high fields.

It appears that the results obtained using the Zeini et al. approach[2] are similar to those obtained with the Krishana et al.[3] for $B \to 0$. The field dependence of $\kappa_{xy}(B)$ is given in good approximation by the function $B/(1+\beta_H B)^2$ where $\beta_H(T)$ is a temperature dependent constant analogous to $\beta_e(T)$, see Eq. (3). Because $\tau_H/m_H \propto \kappa_{xy}/(B\kappa_{xx}^{el})$ and, in principle, $\beta_e(T) \neq \beta_H(T)$, the field dependence of τ_H/m_H can be neglected in the

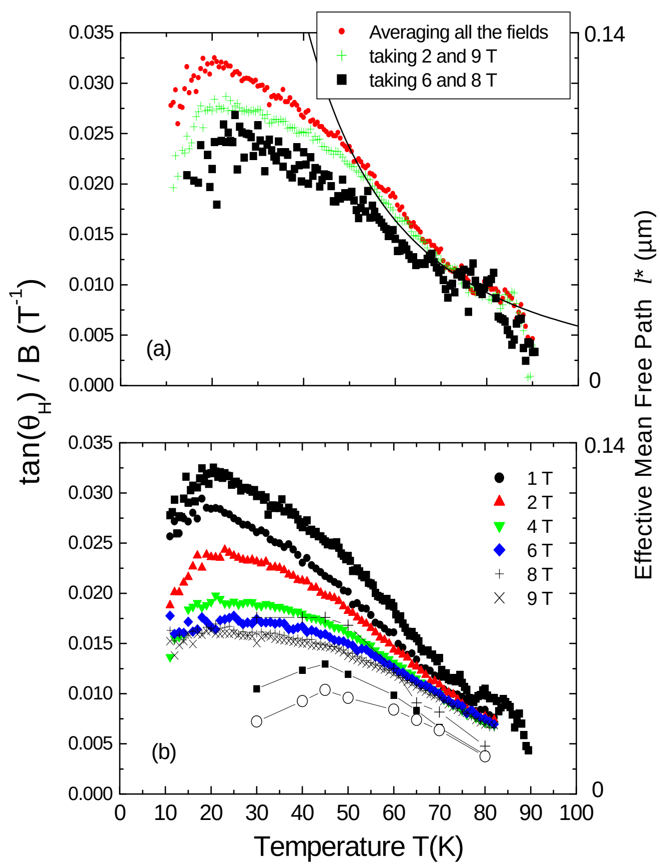


Fig. 3. (a) The ratio $\tan(\theta_H)/B = e\tau_H/m_H$ (θ_H is the Hall angle, e the electron charge, and m_H the mass of the particles responsible for the Hall effect) as a function of temperature obtained assuming a field independent τ_H within the approach of Ref. 2, see Eq. (2). The three curves are obtained averaging the pairs at all measured magnetic fields (•), taking only the values at 2 T and 9 T (+), and at 6 T and 8 T (■). The continuous line has a T^{-2} dependence. (b) The same as (a) at different applied fields calculated using κ_{xx}^{el} obtained by fitting the field dependence of the longitudinal thermal conductivity. (■): Data from (a) averaging all the fields. The three curves with points connected by straight lines are taken from Ref. 3 at $B = 2$ T (+), 6 T (■) and 10 T (◯). The right axis shows the scale of the calculated effective mean free path in μm.

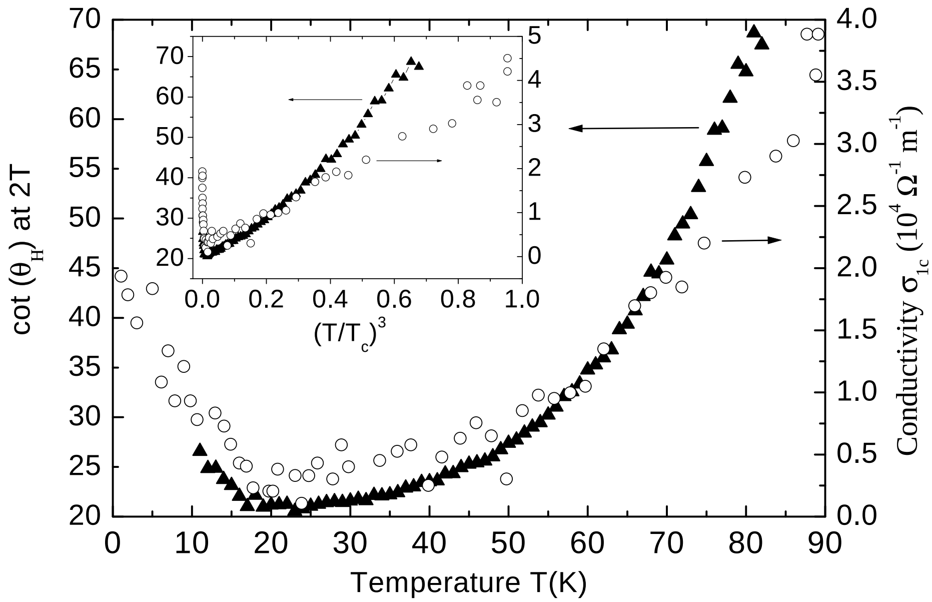


Fig. 4. Temperature dependence of $\cot(\theta_H) \propto m_H/\tau_H$ obtained at $B = 2$ T (▲) and the c-axis microwave conductivity (○, right axis) taken from Ref.[19] Note that the origins of the vertical axes differ. The inset shows the same data but as a function of $(T/T_c)^3$.

limit $B \to 0$. It seems therefore reasonable that in good approximation both approaches provide similar results for the ratio $\tan(\theta_H)/B$ at $B \to 0$.

A rough relationship between $\tan(\theta_H)/B$ and the effective mean free path of quasiparticles can be obtained if we assume that $\tan(\theta_H) \sim \omega_c\tau = eB\tau/m^* \sim eBl/m^*v_F \sim eBl^*/\hbar k_F$. Here v_F and k_F are the Fermi velocity and wave vector, and m^* the effective mass of quasiparticles. Using $k_F \sim 0.6 \times 10^{10}$ m^{-1} we calculate the effective mean free path shown in the right axis scale of Fig. 3.

Figure 4 shows the temperature dependence of $\cot(\theta_H)$ obtained from the data in Fig. 3(b) at $B = 2$ T. We stress that $\cot(\theta_H)$ does not follow the T^2 dependence observed at higher temperatures[2,3] and shows a minimum at $T_m \simeq 20$ K. We note further that the measured temperature dependence of $\cot(\theta_H)$ shows a striking similarity with that measured for the c-axis microwave conductivity obtained at 22 GHz in a Y123 crystal with similar T_c,[19] see Fig. 4. From Ref.[3] we found $T_m \sim 45$ K (see Fig. 2) suggesting that T_m varies from crystal to crystal. A comparison between our results

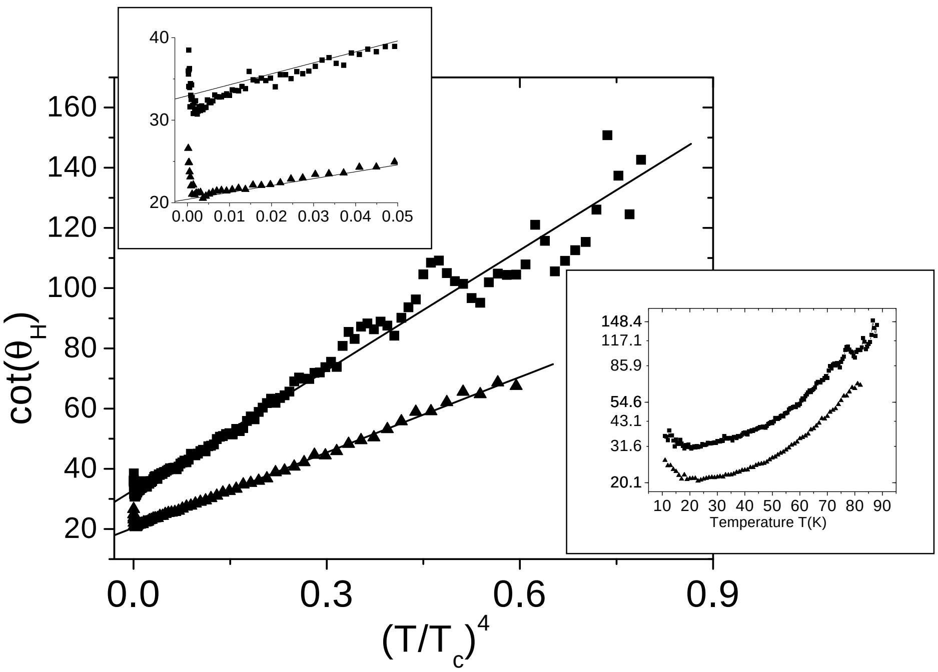


Fig. 5. $\cot(\theta_H) \propto m_H/\tau_H$ obtained at $B = 2$ T (▲) (from Fig. 3(b)) and averaging all the fields (■) (from Fig. 3(a) and assuming $B = 1$ T) as a function of $(T/T_c)^4$. The upper left inset shows the same data at the lowest measured temperatures. The straight lines are linear fits taking into account all the points for $T > T_m$. The botton right inset shows the same data but in a semilogarithmic scale.

and those from Ref.[3] indicates that at high enough fields the difference in the density of scattering centers between samples does not influence the absolute value of θ_H/B significantly, see Fig. 3. It is clear that to demonstrate the possible influence of the sample purity on the mean free path the thermal Hall angle should be obtained at the low-field limit. We note also that the temperature of the minimum in $\sigma_{1c}(T)$ can be shifted from $\sim$20 K to $\sim$40 K depending on the crystal.[19] We will discuss in the next section possible origins of the upturn in $\cot(\theta_H)$.

In a recently published paper[20] it was found that the c-axis conductivity of the crystal reported in Ref.[19] follows approximately a T^3 dependence below T_c and for $T > T_m$, see inset in Fig. 4. This behavior is shown to be consistent with an anisotropic interlayer hopping integral.[20] The authors in Ref.[20] further show that the observed temperature dependence of the $c-$axis conductivity in the intermediate temperature range should be an universal result independent of the scattering rate of quasiparticles. Since

$\cot(\theta_H)$ is directly proportional to the scattering rate of the quasiparticles responsible for the Hall signal and assuming that the result of Ref.[20] is valid, it would be rather surprising if both quantities, $\cot(\theta_H)$ and σ_c, show the same temperature dependence. In fact, we show in the inset of Fig. 4 that $\cot(\theta_H)$ does not follow a T^3 dependence. Our results show that $\cot(\theta_H)$ follows quite accurately a T^4 dependence above T_m and that this dependence is independent of the separation method used, see Fig. 5. The inset at the botton of Fig. 5 shows also that $\cot(\theta_H)$ does not follow an exponential law, $\exp(T/T_0)$, as obtained for the quasiparticle scattering rate from microwave surface resistance using different assumptions.[21] To the best of our knowledge this is the first time that a clear power-law dependence $(T/T_c)^4$ in a broad temperature range is reported for the Hall scattering rate below T_c. This result and the minimum at $T \simeq 20$ K are the main messages of the present work.

The temperature dependence of the quasiparticle scattering rate below T_c is not known at present. From longitudinal thermal conductivity measurements and assuming a $d-$wave pairing Yu et al.[10] obtained a scattering rate that follows roughly a $(T/T_c)^4$ dependence in agreement with our result. On the other hand, since quasiparticle-quasiparticle scattering is the dominant temperature dependent scattering mechanism in our sample, we expect a scattering rate proportional to the density of quasiparticles. In the simple two-fluid model and for an isotropic order parameter we expect a density of quasiparticles proportional to $(T/T_c)^4$.[22]

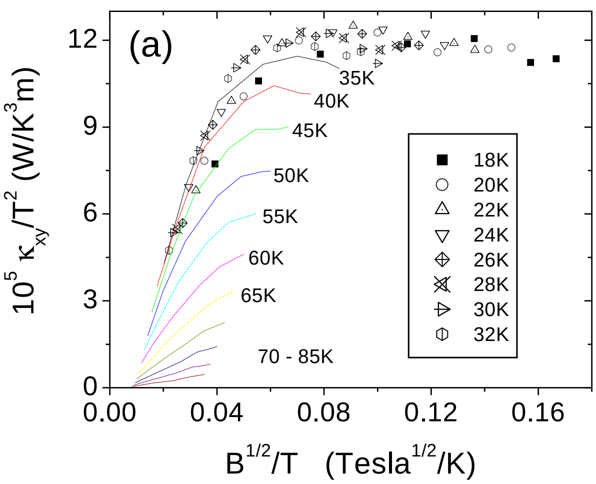
4. Discussion

In this section we restrict ourselves to discuss the nonmonotonic behavior obtained for the Hall angle and its scaling properties. Note first that a simple background scattering contribution to the effective quasiparticle mean free path should saturate $l^*(T)$ at low enough temperatures. However, that $\tan(\theta_H)/B$ shows a nonmonotonic temperature dependence is a nontrivial result not yet clearly reported in the literature. The reason for this temperature dependence is not known at present. Whatever its origin, the results indicate that some additional scattering, change in the quasiparticle density and/or a change in the effective mass takes place below ~ 20 K in our sample. It would be interesting to see whether our results follow the scaling relations for transport properties of d-wave superconductors proposed in the last few years and whether this additional scattering/quasiparticle density or effective mass change has some effect or not.

Volovik and Kopnin[23,24] showed that in unconventional superconductors and because of the presence of low energy excitations associated with the

gap nodes, at low temperatures and low fields ($T \ll T_c, B \ll B_{c2}$) the thermodynamic and transport properties are dominated by the influence of the Doppler shift on the excitation spectrum of the quasiparticles due to the supercurrents flowing around the vortex cores. Simon and Lee[25] predicted a scaling function with only one dimensionless parameter at temperatures below ~ 30 K such that for the heat capacity $C(T,B)/T^2 \propto f(x)$ and the Hall component of the thermal conductivity $\kappa_{xy}/T^2 \propto f_{xy}(x)$ with $x = \alpha\sqrt{B}/T$. The function f and f_{xy} are universal functions. The coefficient α should be equal to $T_c/\sqrt{B_{c2}}$ according to Refs.[26,27] to preserve the correct predicted regimes. Scaling relations can only be extrapolated to the Hall (off-diagonal) component of the thermal conductivity tensor because only this component is electronic in origin. In principle, this picture may also be valid for systems with a 3D order parameter with line nodes such as in UPt_3 as has been shown experimentally.[28] For Y123 crystals the scaling model predicts two changes of regime at the following points: (1) at $x_1 \sim E_F/T_c$ (i.e. at $\sqrt{B}/T \sim 2.18$ Tesla$^{1/2}$/K) where the discreteness of the fermion bound states in the vortex becomes important (the quasiclassical approach does not hold longer) and (2) at $x_2 \sim 1$ (i.e. at $\sqrt{B}/T \sim 0.068$ Tesla$^{1/2}$/K) where the single vortex contribution is comparable to the bulk contribution per one vortex.[26,27]

In Fig. 6(a) and (b) we plot our results following the scaling relation. The points between ~ 18 K and ~ 30 K collapse roughly onto a common curve. A clear deviation for this scaling is observed below 18 K. We note that the predicted crossover at $x_2 \sim 1$ is well reproduced by the data. On the other hand, Hirschfeld et al.[29,30,31] showed that when one treats transport quantities, an exact one-parameter scaling is not necessarily obtained. In fact the account for an impuriy bandwith destroys the scaling properties and a plot of κ_{xy}/T^2 versus the scaling variable x would only yield an approximate scaling in the best case. Either when the impurity band width becomes comparable to the magnetic energy or the temperature or the impurity relaxation rate becomes comparable to the vortex relaxation or inelastic collision rate, scaling should completely break down. This was also pointed out by Won and Maki[32] although in this work the scaling law is recovered in the superclean limit ($\Gamma/\Delta \ll B/B_{c2} \ll 1, \Gamma$ is scattering rate due to impurities in $\hbar$ units). In the clean limit ($B/B_{c2} \ll \Gamma/\Delta \ll 1$) it was shown that the scaling properties break down again. If the used separation procedure to obtain the electronic longitudinal thermal conductivity is really working properly, it should show the same scaling properties as the Hall conductivity. According to Ref.[25] the electronic thermal conductivity κ_{xx}^{el} should show a scaling of the form $\kappa_{xx}^{el}/T \propto f_{xx}(x)$ with $x \propto \sqrt{B}/T$. The results in Fig. 7 indicate that κ_{xx}^{el} shows the same scaling properties as κ_{xy}



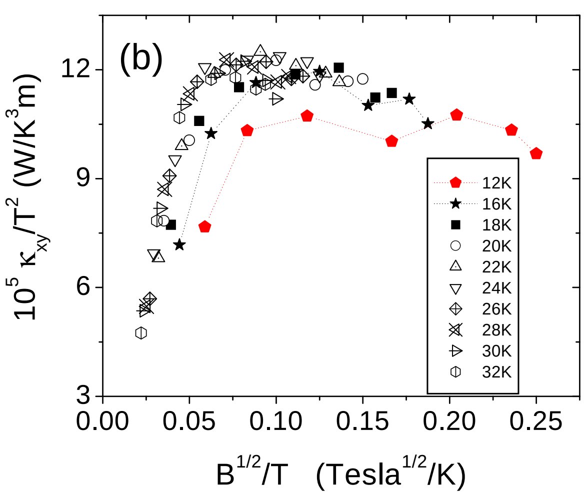


Fig. 6. Hall thermal conductivity divided by the square of the temperature as a function of the scaling variable $B^{1/2}/T$ at different fixed temperatures: (a): 18 K $\leq T \leq$ 85 K; (b): 12 K $\leq T \leq$ 32 K.

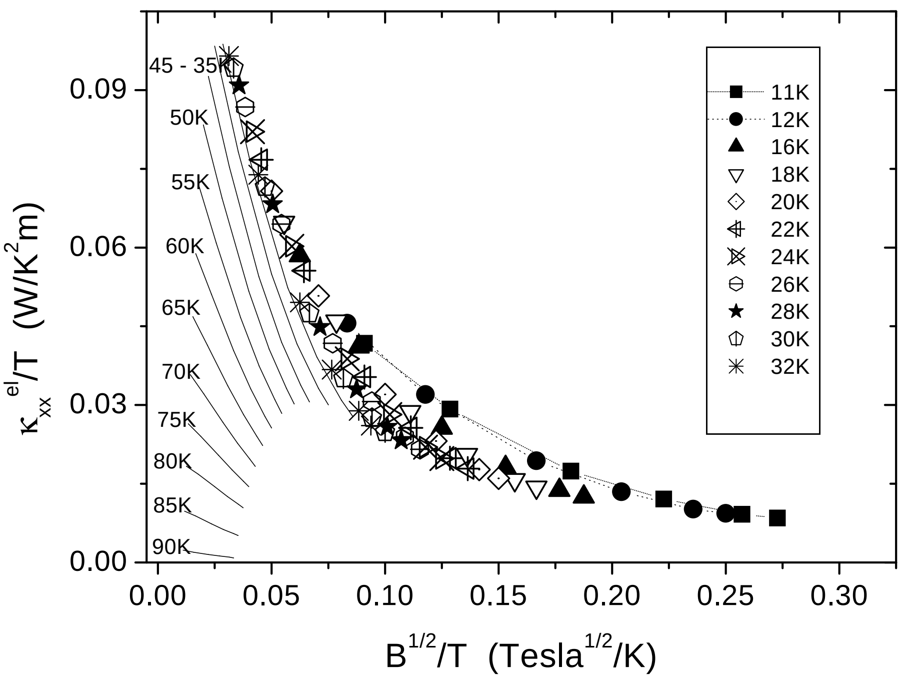


Fig. 7. Longitudinal electronic thermal conductivity divided by the temperature as a function of the scaling variable $B^{1/2}/T$ at different fixed temperatures. At 18 K $\leq T \leq$ 32 K κ_{xx}^{el} shows the predicted scaling behavior.

in the same temperature range.

In conclusion, we think that our results for the electronic part of the longitudinal and the Hall component of the thermal conductivity on a Y123 crystal do show a convincing scaling in a restricted temperature range only. While the experimental points between 30 K and 18 K collapse roughly onto a common curve, the ones below and above this range spread out. This result partially contradicts the experimental results shown in Ref.[27] since in that work no data were taken below 20 K. On the other hand the picture of an approximate scaling proposed first by Kübert and Hirschfeld[29] and later by Won and Maki[32] appears to be consistent with our experimental data implying that an additional scattering/quasiparticle density or effective mass change should be taken into account for the calculation of transport properties on these systems.

The observed upturn in the c-axis conductivity at $\sim$ 20 K, see Fig.4, is not yet understood.[19,20] Because the c-axis conductivity decreases with

temperature at $T < T_m$ it seems reasonable to conclude that the accompanied anomaly in $\theta_H(T)$ is not related to the crossover from holon non-drag to a localization regime.[4] Experimental results indicate that below T_c the c-axis conductivity shows a clearly different behavior as the ab-plane conductivity, an experimental fact used as evidence for incoherent transport between CuO_2 planes.[19] A possible crossover to coherent transport at T_m is, however, not yet clarified.[20] Ioffe and Millis[33] pointed out that the $c-$axis conductivity involves mainly the scattering mechanism of electrons within a CuO_2 plane. From this point of view appears reasonable to search for a common origin of the anomaly at T_m observed in the $c-$axis conductivity and the Hall signal. However, this appears to be in contradiction to the different behavior of the electrical transport properties cited above. This apparently contradictory behavior may be related to the influence of the interlayer hopping integral on the $c-$axis transport properties. According to Xiang and Hardy[20] the anisotropy of this hopping integral affects in such a way the $c-$axis conductivity that it does not depend on the quasiparticle scattering rate and an universal T^3 dependence below T_c is obtained in agreement with the experimental results.

Electrical Hall angle measurements in different HTS[5,6,7] show a clear minimum in $\cot(\theta_H)$ above T_c which has been identified as the opening of the pseudogap. Therefore, we may speculate that this opening occurs at T_m where $\cot(\theta_H)$ shows a clear minimum, see Fig. 4. We note that the opening of a pseudogap *below* T_c in Y123 HTS appears to be supported by different experimental results.[8] Supporting such a scenario, the opening of a charge density wave gap at $T < 35$ K has recently been reported for Y123 crystal with $T_c \simeq 90$ K.[34] Does the opening of a pseudogap influence the scattering rate τ_H^{-1} or the effective mass m_H ? Since in a simple picture one expects the decrease of the scattering rate when the pseudogap opens, it has been suggested that the pseudogap affects $\cot(\theta_H)$ through a change in the effective mass which may be related to a modification in the Fermi surface topology.[6] The correlation between Hall angle and c-axis conductivity shown in the present work would suggest that the pseudogap influences the c-axis conductivity as well. If the scattering rate independence of the $c-$axis conductivity[20] would remain valid at and below T_m, the correlation implies that the a similar mechanism that changes the effective mass at T_m would be responsible for the upturn in the c-axis conductivity. We note, however, that experimental results in $Bi_2Sr_2CaCu_2O_8$ HTS indicate that the opening of the pseudogap reduces the $c-$axis conductivity in the normal state.[35] Future experiments should clarify if this behavior is also observed in Y123 HTS and below T_c.

5. Conclusion

In summary, we have measured the longitudinal and transverse thermal conductivity of a twinned and nearly optimally doped Y123 crystal as a function of temperature at different applied fields. We have used two different approaches to derive the temperature dependence of the Hall angle. Independently of the approach, we observe that $\cot(\theta_H)$ does not follow a T^2 dependence but a T^4 dependence at $T/T_c >\sim 0.3$, reaching a minimum at $T \sim 20$ K. The T^4 dependence agrees with the dependence of the scattering rate obtained from longitudinal conductivity measurements.[10] The anomaly of $\cot(\theta_H)$ observed at 20 K resembles that of the c-axis conductivity of a optimally doped crystal with similar T_c. Based on the proved sensitivity of the Hall angle to the pseudogap[5,6,7] we may speculate that this behavior reflects the opening of the pseudogap at temperatures much below T_c. We showed also that the electronic longitudinal and the thermal Hall conductivity show a scaling only in a restricted temperature range. This scaling breaks down at temperatures $T < 18$ K, where the Hall angle changes its behavior, and at $T > 30$ K.

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